ERDC/CHL CHETN-IV-47
June 2002

US Army Corps of Engineers®

Tidal Velocity Asymmetry at Inlets

by Todd Walton

PURPOSE: The Coastal and Hydraulics Engineering Technical Note (CHETN) herein discusses selected factors responsible for controlling tidal velocity asymmetry at tidal inlets with implications for maintenance of navigation channels and sediment bypassing to the adjacent beaches.

BACKGROUND: Navigation improvements, such as channel widening, channel deepening, and bay island building from dredged material will alter the hydraulics of an inlet and may lead to change in the long-term morphological evolution of the inlet complex and its adjacent beaches. Such changes may initiate unplanned dredging requirements in the inlet system as well as in the navigation channel. Sediment transport is related in a nonlinear way to velocity; hence, tidal velocity asymmetry at inlets influences the predominant flow direction of sediment transport into and out of the inlet system. Previous researchers (e.g., Pingree and Griffiths 1979) have found sand transport direction coinciding with asymmetries in the tide caused by harmonic tidal constituent interaction. Asymmetry in sea level and currents (and resulting sediment transport fluxes) therefore determines how the inlet/estuary system will evolve in time. Inlets with flood currents greater than ebb currents are more prone to build larger flood shoals, denying sand to the seaward beach system, whereas ebb-dominant systems flush sediment seaward helping to maintain a more efficient inlet and corresponding navigation channel.

INLET SYSTEM DEFINITION: The inlet-bay system considered in this technical note is similar to that defined in Keulegan (1967) and Headquarters, U.S. Army Corps of Engineers (2002) which consists of a channel (with length L and cross section A_c) connecting a bay (with surface area A_b) to the open ocean. In the simplest case discussed, the bay area is constant and has a uniformly fluctuating water level, and the cross section of the channel area is constant. Additional work by various researchers that considers bays with time-varying bay surface areas and time-varying channel cross sectional areas will also be discussed.

DEFINITION OF TIDAL ASYMMETRY: This technical note discusses the situation whereby the total flow (= $u(t)A_c$ = inlet velocity multiplied by the channel cross section) through an inlet integrated over a tidal cycle is zero (i.e., continuity requirement for no inflow or outflows from bay-channel complex). If the duration of the falling tide exceeds that of the rising tide leading to a larger peak flood current (higher cross-sectional averaged peak flood velocity), the system is referred to as flood dominant or flood asymmetric. If the duration of the falling tide is shorter than that of the rising tide leading to a stronger peak ebb current, the system is referred to as ebb dominant or ebb asymmetric.

Other factors for asymmetry in temporal ebb and flood currents may exist at an inlet and, additionally, other types of asymmetries (spatial asymmetry in inlet ebb and flood channels) may be present. Temporal ebb current dominance has been noted in flow over two tidal cycles as produced by strong offshore-directed winds where the inlet system (East Pass, FL) consisted of a large relatively shallow bay system and the wind was blowing offshore. Velocity asymmetry can also

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2002**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE
Tidal Velocity Asymmetry at Inlets (ERDC/CHL CHETN-IV-47)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Walton, Todd

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
This Coastal and Hydraulics Engineering Technical Note (CHETN) discusses selected factors responsible for controlling tidal velocity asymmetry at tidal inlets with implications for maintenance of navigation channels and sediment bypassing to the adjacent beaches.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**17**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

exist over the vertical profile of the current with strongest ebb current running at a different level than flood current. This is most apparent at inlets where freshwater discharge is a factor and stronger ebb current (less dense fluid) tends toward the surface while stronger flood currents (i.e., greater density fluid) runs deeper (Ippen and Keulegan 1965). This vertical asymmetry effect would enhance sediment movement into the inlet system.

Additional reasons for asymmetry in tidal ebb and flood flow have been mentioned in the literature for river inflow to the bay system (Escoffier and Walton 1979), and construction of tidal gates (Costa and Isaacs 1975), but these effects will not be discussed in this technical note. An example of one type of spatial velocity asymmetry is shown at Shinnecock Inlet, NY, in Figure 1 (from Militello and Kraus 2001) where ebb channels adhere to the bay shoreline while the flood channels extend over the flood shoals. Similar flood channels adjacent to the shoreline are usually seen on the ocean side of inlets where inlets do not have jetties or terminal groins cutting off this potential flow pattern (Dean and Walton 1975). Where channels exist along the margins of the inlet there will be correspondingly less flow in the main channel over the outer ebb shoal channel (in the case of nearshore flood channels on the seaward side of the inlet) and over the inner flood shoal channel(s) (in the case of nearshore ebb channels on the bay side of the inlet). Another type of spatial velocity asymmetry is apparent at Barnegat Inlet, NJ, in Figure 2 (from Seabergh, Cialone, and McCormick, in preparation) where a flood channel runs along the south jetty and an ebb channel runs along the north jetty. In this particular situation, the asymmetry in flow has caused scour potential patterns that could threaten the jetty structures.

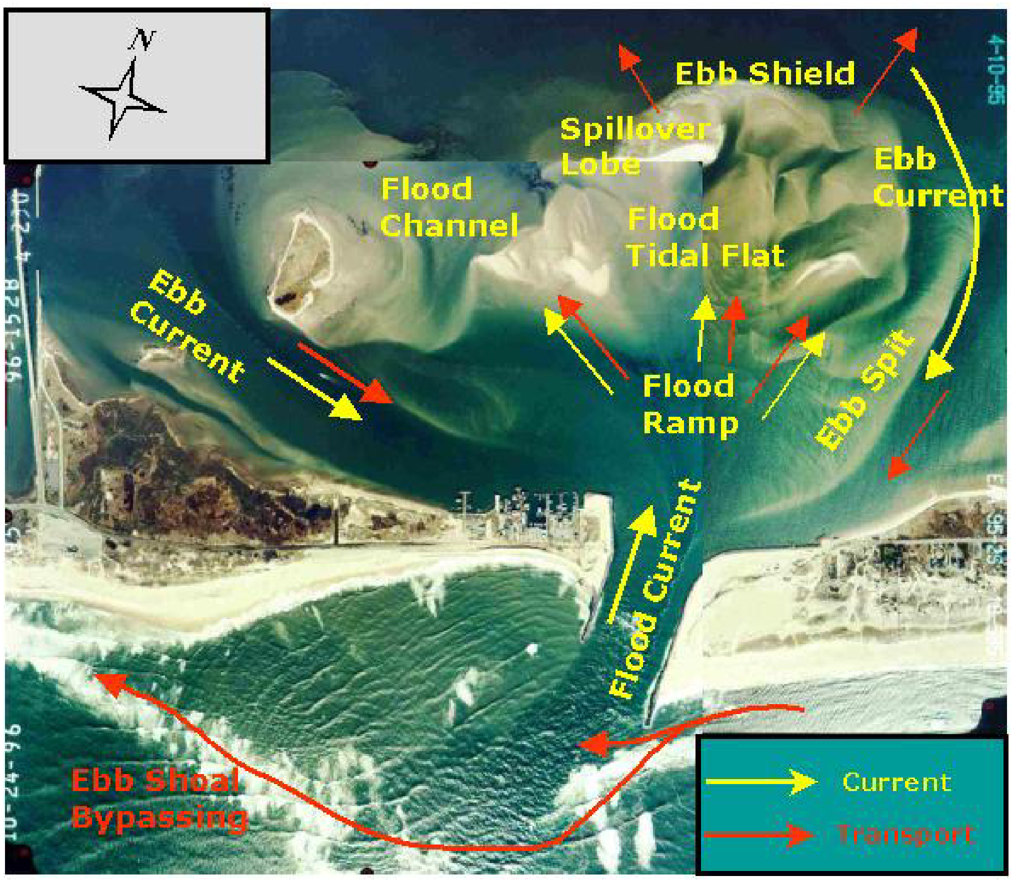


Figure 1. Flood and ebb channels on the bay side of Shinnecock Inlet

Figure 2. Barnegat Inlet, NJ

For this technical note, asymmetry is defined in terms of channel tidal velocity asymmetry, because channel tidal velocity $u(t)$ is considered to be a driving force for sediment transport within the system. Typically (bed-load) sediment transport is related to current velocity in a nonlinear fashion via an equation of form (Fry and Aubrey 1990):

$$q(t) = C(u(t)^2 - u_{cr}(t)^2)^n \tag{1}$$

where

$q(t)$ = (bed-load) sediment transport through the inlet

C = empirical coefficient (constant)

$u(t)$ = inlet channel velocity

$u_{cr}(t)$ = critical threshold velocity of sediment (typically 20 to 30 cm/sec for sand)

n = positive number(on the order of 3/2).

Although continuity of flow (assuming no inflow/outflow into bay system and constant cross-sectional channel area) requires that the integral of $u(t)$ over a tidal cycle be zero, no such constraint is imposed on velocity with an exponent larger than 1. An asymmetric tidal velocity record consisting of larger peak flood (directed toward the bay) velocity (and of shorter duration in time)

that is balanced (continuity wise) by a smaller peak ebb (directed toward the ocean) velocity (and of longer duration in time) will lead to a positive value of the integral of Equation 1 and consequent net (bed-load) sediment flux toward the bay (flood dominance). A similar argument with longer flood velocity duration and higher peak ebb velocity leads to ebb dominance and net bed-load sediment flux toward the ocean.

Because the type of inlet system considered here has predominately one-dimensional flow in the connecting channel between the inlet and bay, there are two possible types of inlet tidal velocity asymmetry depending on the peak channel tidal velocity:

a. Flood-dominant asymmetry in which the net (bed-load) sediment transport (sediment transport averaged over a tidal cycle) would be directed toward the bay, tending to enhance the development of larger flood shoals within the bay system.

b. Ebb-dominant asymmetry in which the net sediment transport (sediment transport averaged over a tidal cycle) would be directed toward the ocean, tending to enhance the development of the inlet ebb shoal.

The relationship between the bay tide and the channel velocity is given (Keulegan 1967) via the inlet continuity equation:

$$u(t) = \frac{A_b}{A_c}\frac{dh_b(t)}{dt} \qquad (2)$$

As a consequence of the preceding continuity equation, knowledge of the bay tide $h_b(t)$ can provide knowledge of the channel velocity $u(t)$. This relationship will be used in the following section to demonstrate phasing requirements of bay tide harmonic components necessary for flood and/or ebb dominance under simplified tidal forcing.

ASYMMETRY DUE TO TIDAL HARMONIC CONSTITUANTS IN FORCING TIDE: The principal astronomical ocean tidal constituents are different for various coastal areas depending on the type of tide. Along the east coast of the United States, semidiurnal tides with a large M_2 component prevail, whereas along the Gulf of Mexico diurnal tides predominate along with mixed tides in certain areas (HQUSACE 1989, 1991). On the west coast of the United States, mixed tides consisting of a combination of diurnal and semidiurnal characteristics exist (HQUSACE 1989, 1991). Seelig and Sorenson (1978) applied a one-dimensional numerical model of a simplified inlet-bay system and found that an ocean tidal asymmetry characteristic of an East Coast location with predominantly semidiurnal tides (Wilmington, NC) favored flood dominance. They also noted that the ocean tide asymmetry characteristic of a West Coast location with mixed tides (Los Angeles, CA) favored ebb dominance. Using the same numerical model, Seelig and Sorenson (1978) also found that ocean hydrographs characteristic of (large) storm surges lead to flood dominance during the surge.

An additional mechanism for tidal velocity asymmetry in inlet systems is the presence of the higher harmonics of the principal astronomical ocean tidal constituents (Boone and Byrne 1981; Aubrey and Speer 1985; DiLorenzo 1988). A higher harmonic of a principal tidal component is a second

harmonic component having an exact integer multiple frequency of the principal component frequency. These higher harmonic tidal components are often referred to as "overtides" and are created by nonlinear distortions of the tidal wave as the tide propagates into shallow water.

As a simple example of forcing tide asymmetry caused by higher harmonics (overtides), a channel velocity might consist of two tidal components, a predominant semidiurnal M_2 constituent (HQUSACE 1989) having a period of approximately 12.4 hr, and its first harmonic, the M_4 constituent (with a corresponding period of approximately 6.2 hr). The tidal velocity so described can be written as follows:

$$u(t) = U_{M2}\cos(\omega t) + U_{M4}\cos(2\omega t - v_{M4}) \tag{3}$$

where

U_{M2} = amplitude of M_2 velocity component of tide

U_{M4} = amplitude of M_4 velocity component of tide

v_{M4} = velocity phase difference between M_2 and M_4 velocity constituents of tide.

Correspondingly, a relationship for the bay tide water level is:

$$h_b(t) = A_{M2}\cos(\omega t) + A_{M4}\cos(2\omega t - g_{M4}) \tag{4}$$

where

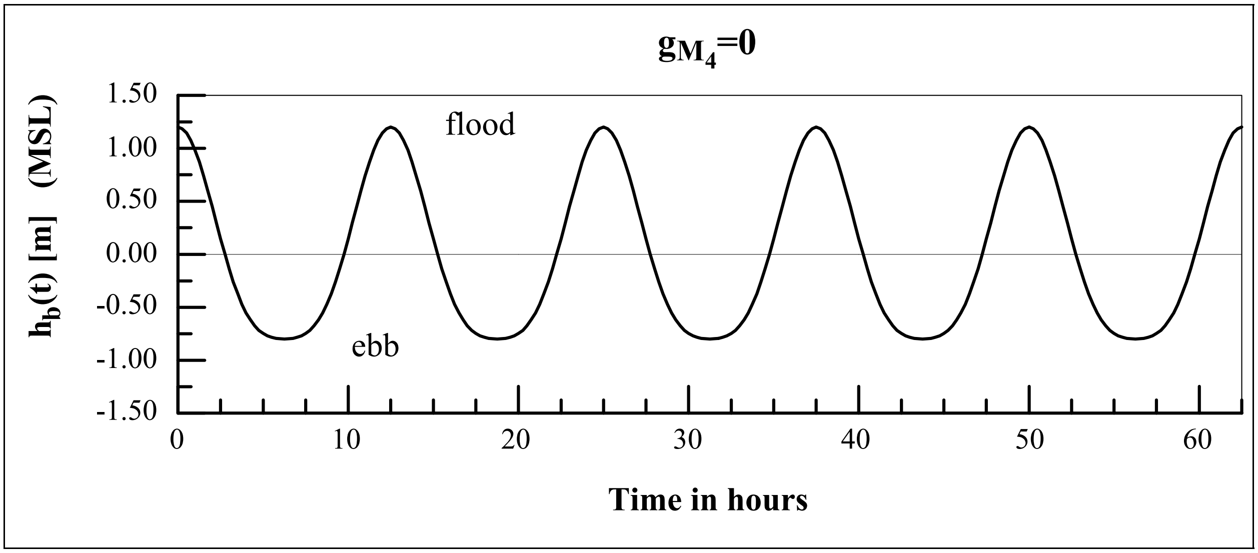
A_{M2} = amplitude of M_2 component of tide

A_{M4} = amplitude of M_4 component of tide

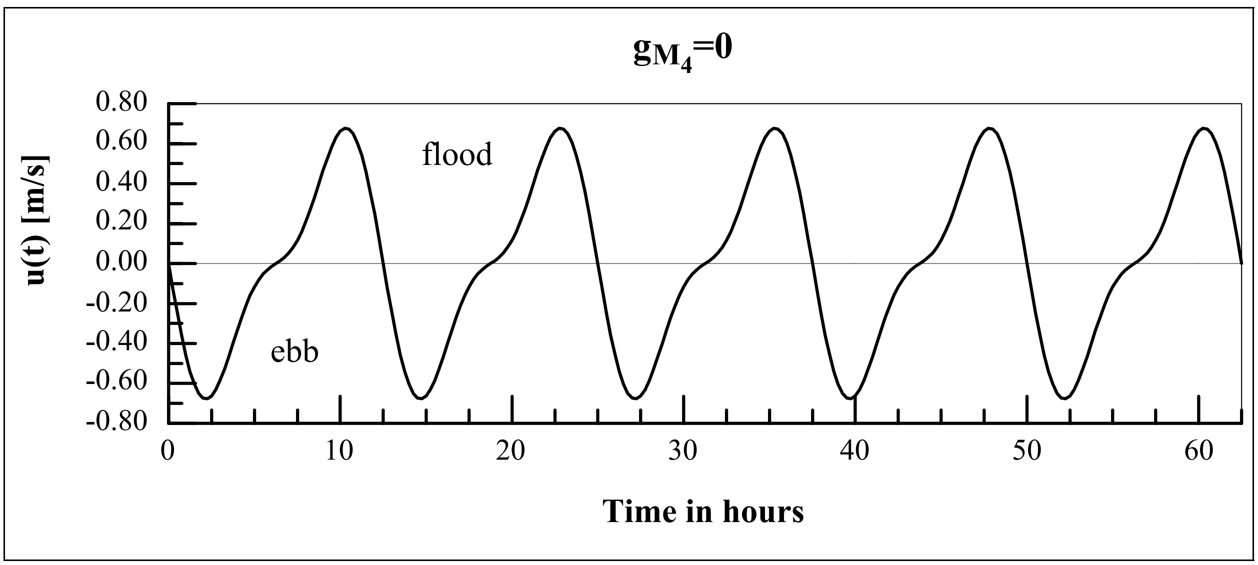
g_{M4} = amplitude phase difference between M_2 and M_4 constituents of tide, where the bay tide can be related to the channel velocity through the inlet continuity equation.

Examples of bay tide water level and channel velocity records with $A_{M2} = 1$ m, $A_{M4} = 0.2$ m, and four different amplitude phase angles $g_{M4} = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$ are provided in Figures 3 through 6 where the bay surface area $= 1{,}000{,}000$ m^2 and the cross-sectional inlet area $= 250$ m^2. Part (a) of each figure is the water level record with respect to mean sea level (msl) vs. time. Part (b) of each figure is the velocity record vs. time. Each figure is plotted over five tidal cycles (where M_2 tidal period = 12.42 hr).

Figures 3a and 3b show the water level vs. time and the velocity vs. time through five tidal cycles where $g_{M4} = 0$. There is no dominance in flood or ebb (symmetric flood and ebb velocities). Flood velocities are denoted as positive for direction toward the bay whereas ebb velocities are negative (flow directed toward the ocean).



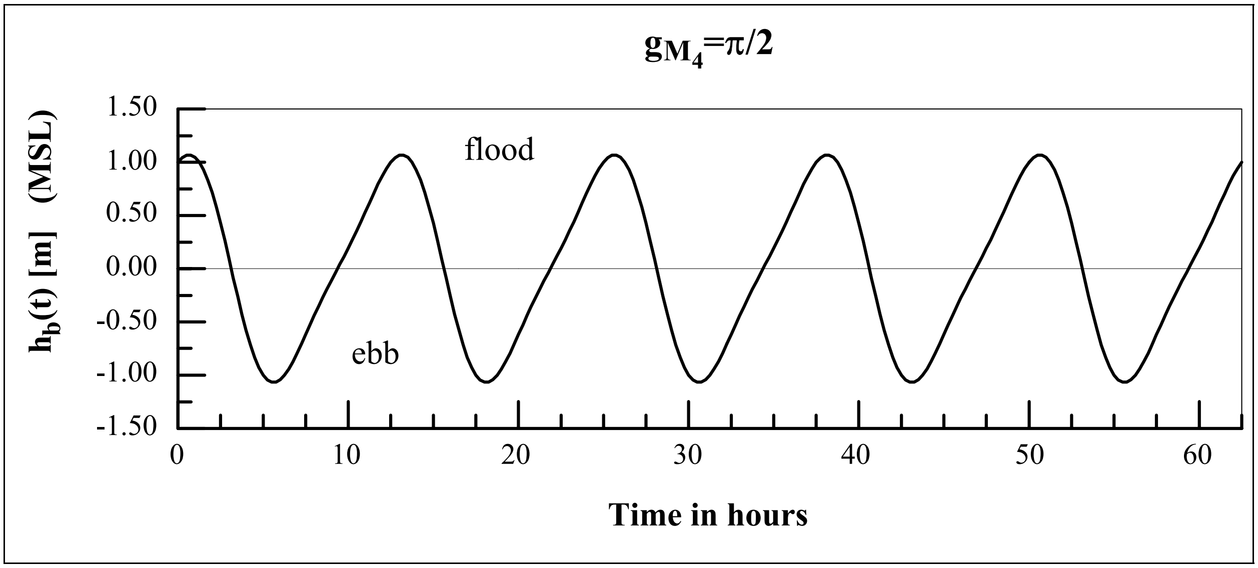
a. Bay water level vs. time (phase lag = 0 deg)



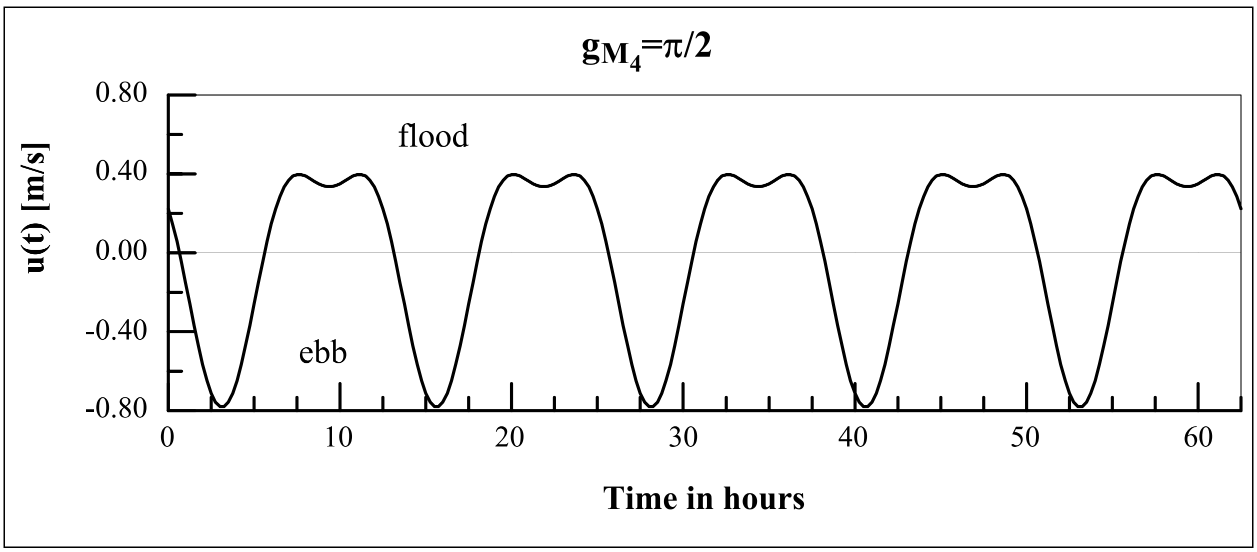
b. Channel velocity vs. time (phase lag = 0 deg)

Figure 3. Water levels and currents vs. time (phase lag = 0 deg)

Figure 4a and 4b correspond to phasing $g_{M4} = \frac{\pi}{2}$. The velocity record shows an ebb-dominant behavior with larger peak ebb currents (asymmetric velocity record).



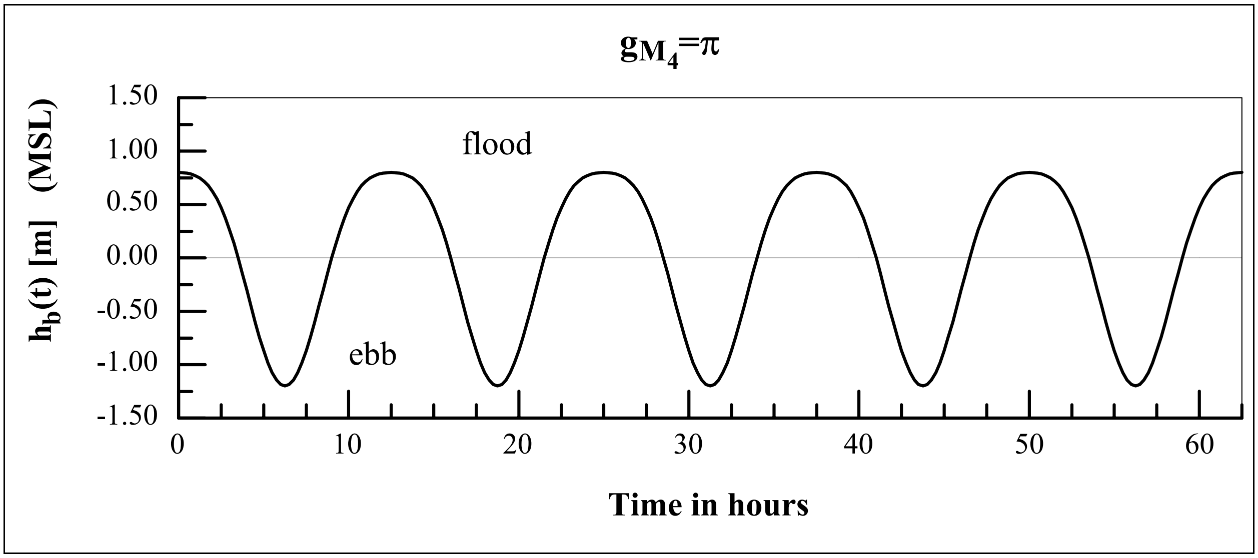
a. Bay water level vs. time (phase lag = 90 deg)



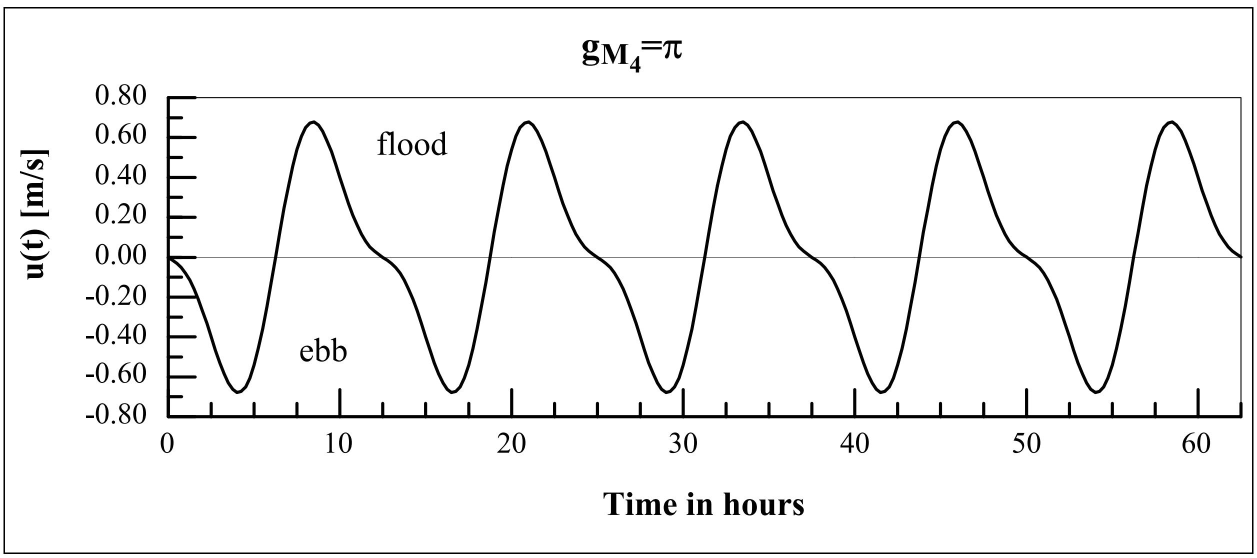
b. Channel velocity vs. time (phase lag = 90 deg)

Figure 4. Water levels and currents vs. time (phase lag = 90 deg)

Figure 5a and 5b show the situation for phasing $g_{M4} = \pi$. The velocities show no dominance in flood or ebb (symmetric velocity record).



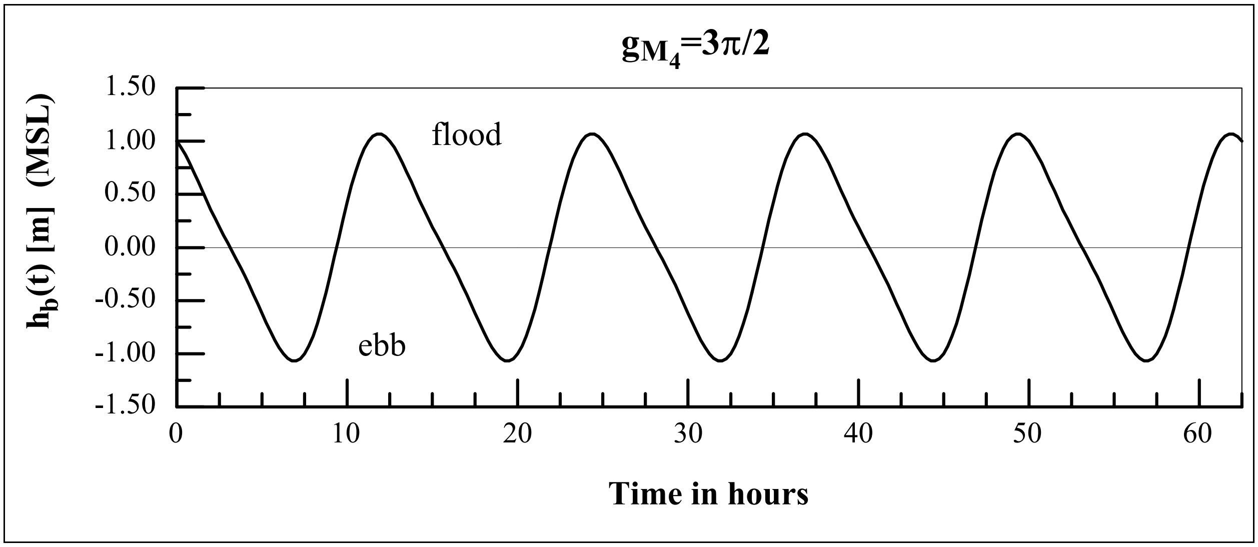
a. Bay water level vs. time (phase lag = 180 deg)



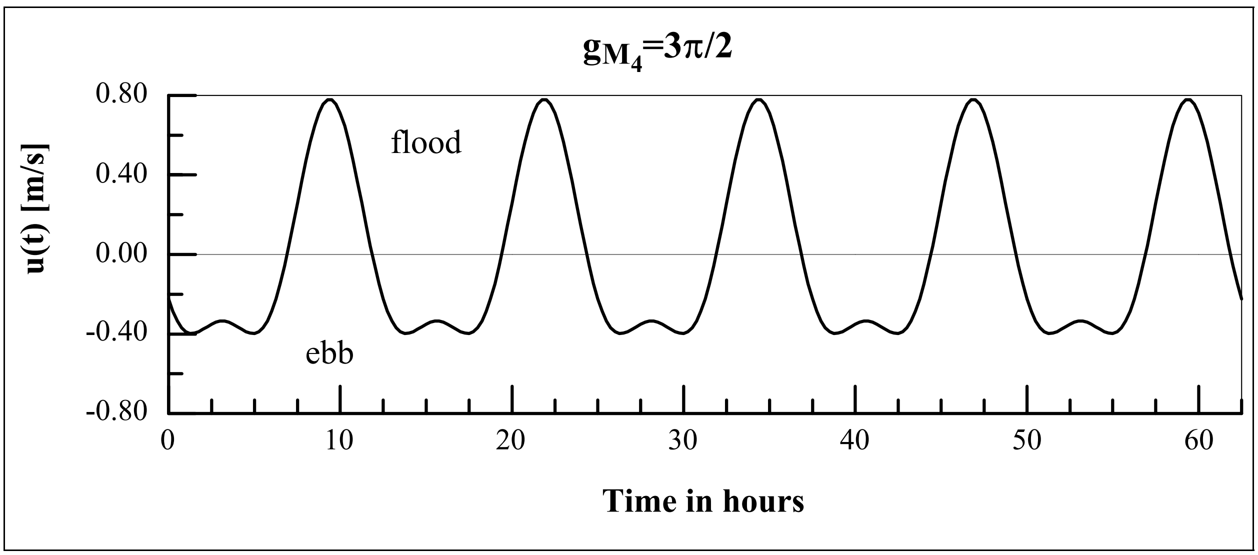
b. Channel velocity vs. time (phase lag = 180 deg)

Figure 5. Water levels and currents vs. time (phase lag = 180 deg)

Figure 6a and 6b show the situation for phasing $g_{M4} = \frac{3\pi}{2}$, where velocities show flood-dominant behavior (asymmetric velocity record).



a. Bay water level vs. time (phase lag = 270 deg)



b. Channel velocity vs. time (phase lag = 270 deg)

Figure 6. Water levels and currents vs. time (phase lag = 270 deg)

Boon and Byrne (1981) showed that for the simplified inlet definition of Keulegan (1967) with a bay tide relationship given by

$$h_b = A_{M2}\cos(\omega t) + A_{M4}\cos(2\omega t - g_{M4}) \tag{5}$$

that flood dominance exists if $\pi \le g_{M4} \le 2\pi$, and ebb dominance exists if $0 \le g_{M4} \le \pi$. Additionally, the greater the ratio $\frac{A_{M4}}{A_{M2}}$, the greater the flood or ebb dominance.

Aubrey and Speer (1985) note similar relationships controlling the flood or ebb dominance of an inlet-bay system due to higher harmonics in the ocean forcing tide.

DiLorenzo (1988) using a nonlinear analytical model of a Keulegan type inlet-bay system with constant channel cross section and constant bay surface area (but with ocean tide consisting of a sinusoid and its higher harmonic) found that asymmetry can be introduced due to the higher harmonic. Using a forcing ocean tide consisting of two constituents (M_2 and M_4) he found that flood or ebb dominance was controlled by the phasing between the two constituents.

Ranasinghe and Pattiaratchi (2000) found via 30-day measurements in three inlet systems studied that the ocean forcing tide harmonics and their phasing relationships were the major factors controlling the velocity asymmetry in the inlet systems studied. The three systems studied in Ranasinghe and Pattiaratchi (2000) had the common characteristics of primarily diurnal tidal forcing and morphology consisting of a wide shallow basin connected to the ocean via a narrow inlet channel. In two of the inlet systems studied, the ocean forcing tide asymmetry was such that ebb dominance was apparent while the third inlet had a flood-dominant asymmetry. Ranasinghe and Pattiaratchi (2000) concluded that a simple phase angle relationship to predict flood/ebb dominance does not exist for diurnal systems. The oceanic tides along the southwest Australia coast where the study was conducted are mainly diurnal with maximum tidal ranges of around 0.8 m. Because estuarine tidal ranges are small, intertidal flats are almost nonexistent in the three systems studied. The Ranasinghe and Pattiaratchi (2000) analysis shows that the occurrence of flood/ebb dominance at diurnal tidal inlets, where there are no tide-distorting nonlinear mechanisms, can be predicted by using oceanic tidal elevations as well as tidal velocities.

OTHER CAUSES OF TIDAL ASYMMETRY IN INLETS: Typically, at inlets where cross-sectional area of the channel and the bay area change with the tidal cycle, other factors can contribute to the asymmetry of the channel tidal current.

Asymmetry Generated by Friction. Mota Oliveria (1970) concluded by energy equation considerations that head losses associated with higher friction in the inlet channel should bring about a decrease in bay tidal prism and consequent decrease in natural flushing capacity. His hypothesis suggests that greater friction moves an inlet system toward flood-dominant behavior.

Seelig and Sorenson (1978) found via numerical model simulations that greater friction (higher values of Manning coefficient in their model) leads to increasing flood dominance in the system. As their friction factor was made to weakly decrease with (increasing) channel depth, their results suggest that shallower channels are more flood dominant than deeper channels.

Speer and Aubrey (1985) and Aubrey and Speer (1985) also found via numerical modeling simulations a trend toward flood dominance in shallow channels where friction increases as a function of decreasing water depth. At Nauset Inlet, MA, Speer and Aubrey (1985) conducted a tide and current measurement program and noted that the inlet was controlled by the M_2 and M_4 tidal constituents and that the factor controlling the direction of the tidal asymmetry (flood or ebb dominance) was the phase difference between the M_2 and M_4 tidal constituents. In the shallowest channels where friction was highest, Speer and Aubrey (1985) measured rapid amplitude decay of the primary tidal constituent with over 50-60 percent of the tidal range lost over a channel distance

of 5-6 km. In the same channel length the higher harmonic overtide component increased. In one measurement period large phase changes (~76 deg) in the M_2 tidal constituent and amplitude decay of the total spectrum (~57 percent) were seen within a 2-km distance. They attributed the flood dominance of this inlet/estuary (in part) to high channel friction. Speer and Aubrey (1985) found in general that stronger friction produced larger M_4/M_2 ratios, and phasing differences between M_4 and M_2 constituents consistent with flood dominance.

In accord with the numerical findings of Speer and Aubrey (1985), Aubrey and Speer (1985), and Seelig and Sorenson (1978), and the energy equation arguments of Mota Oliveria (1970), one would expect inlets with deeper (efficient) channels (clear of sand waves) would be more prone to ebb dominance than shallow rough bed channels, and correspondingly, that channels with higher friction would be more prone to flood dominance.

Asymmetry Generated by Tidal Interactions with Estuarine/Inlet Channel Geometry. Changing channel geometry with time can also influence asymmetry. Considering the inlet continuity equation given previously, for which $\frac{dh_b}{dt} \sim \frac{A_c}{A_b}$, if A_b is held constant and A_c increases with the rising tide, then the rate of rise increases, while the rate of fall decreases over time. This means there is a shorter rise and slower fall time, indicating greater flood velocity peaks (assuming the same volume of water entering and leaving the bay), and a resulting flood dominance when considering only time varying channel cross section.

Based upon limited numerical modeling results, Gallagher (1973) found that in the two cases he studied, flood dominance occurred because of including an increasing channel cross section with tidal stage.

Mota Oliveria (1970) simulated (via numerical modeling) inlet systems similar to those considered by Keulegan (1967) (constant bay area with tidal stage) only with channel depth change varying with tide stage. He observed that in inlet systems with a Keulegan repletion coefficient (HQUSACE 2002) greater than 0.8 the inlet systems tended to be flood dominant while for inlet systems with a Keulegan repletion coefficient less than 0.6, that the inlet systems tended to be ebb dominant.

Speer and Aubrey (1985) found via numerical modeling experiments that increasing the ratio of tidal amplitude to water depth while keeping friction constant moved the inlet system in a flood-dominant direction and enhanced the growth of the M_4/M_2 ratio (Characteristic values of the amplitude/depth ratio ranged from 0.1 to 0.5 in Speer and Aubrey (1985) numerical experiments). Ratios of $a/d >$ 0.3 (where a = tidal amplitude and d = channel depth) were found to lead to flood dominance while ratios of $a/d < 0.1$ (with large areas of tidal flats) were found to be ebb dominant. In a similar manner, they found that increasing the channel side slope whereas keeping friction constant moved the inlet system in a flood-dominant direction.

Speer and Aubrey (1985) additionally found (via means of numerical model simulations) that channels without channel tidal flats (portion of channel bed intersected between high and low tide) developed a time asymmetry predominantly characterized by a longer falling tide than rising tide, and consequent flood dominance in tidal flow. In the same studies, Speer and Aubrey (1985) found that (significant) tidal flats within the channel area could shift the phase difference to that of ebb

dominance for the system investigated. Additionally, Speer and Aubrey (1985) found that time-variable channel geometry may be a source of harmonic (overtide) growth because channel perimeter (and hence, overall friction) changes at different rates over the tidal cycle.

DiLorenzo (1988) based on simple arguments using a nonlinear expansion of the momentum equation noted that increasing channel cross-section variability with tide stage moves the inlet-bay system in the direction of flood dominance.

Conclusions based on these geometrically changing channel studies suggest that increasing cross-sectional area with tidal stage (except for tidal storage areas) moves the inlet in a flood-dominant direction. It is also clear that increasing the channel tidal flat storage areas moves the inlet system in an ebb-dominant direction.

Asymmetry Generated by Basin Hypsometry. Basin (bay) hypsometry is defined as the vertical distribution of basin (bay) surface area with height (i.e., see Boon and Byrne 1981; Dronkers 1986; van de Kreeke 1988). Correspondingly, the area of the basin situated between high and low tide is referred to as tidal flat. When the bay water surface area increases with tidal elevation, asymmetry of an ebb-dominant form may be produced (Boon and Byrne 1981; FitzGerald and Nummedal 1983). In inlet systems with open bays (no tidal flats) or bays filled by high marsh, tidal asymmetry of a flood-dominant form may be more likely to occur (Mota Oliveria 1970; Seelig and Sorenson 1978; and Speer and Aubrey 1985). A physical argument for this effect can be made by considering the inlet continuity equation, where $\frac{dh_b}{dt} \sim \frac{A_c}{A_b}$. If A_b increases with the rising tide while A_c is held constant, then the rate of rise decreases, while the rate of fall increases over time. This means there is a longer rise time and faster fall time, indicating ebb velocity peak larger than flood velocity peak (assuming the same volume of water entering and leaving the bay), and a resulting ebb dominance.

Mota Oliveria (1970) simulated inlet systems via numerical modeling and observed that the inlet systems moved toward an ebb-dominated system as the slope of the bay/lagoon area increased (i.e., as tidal flats increased). In this particular set of simulations, Mota Oliveria (1970) assumed a linearly varying bay water surface area with tidal elevation.

Nummedal and Humphries (1978) and FitzGerald and Nummedal (1983) have suggested that duration asymmetry in tidal flow is controlled by the variation in estuarine/bay surface area relative to the inlet cross-section area.

Seelig and Sorenson (1978), utilizing both linear and exponential bay water surface area variation with tidal elevation in numerical model simulations, found that increasing the bay water surface area with tidal elevation moves the inlet system toward ebb dominance.

Based on numerical simulations, Boon and Byrne (1981) noted that during the early stages of bay evolution, the duration of the flood tide is shorter than that of the ebb tide producing faster velocities on the flood (flood dominance) and the bay tends to fill with sediment. As the bay fills in with sediment, they postulated that the duration of the flood tide becomes longer, resulting in longer flood durations and consequent faster ebb velocities (ebb dominance). Boon and Byrne (1981) suggest

that a flood-dominant inlet-bay system will evolve into an ebb dominant inlet-bay system as sediment infilling within the system increases the tidal flat area within the basin.

Based on interpretation of a nonlinear expansion of the momentum equation, DiLorenzo (1988) noted that increasing bay water surface area with tide stage moves the inlet-bay system in the direction of ebb dominance.

As the propagation of the tide into an inlet/lagoon/estuary is depth-dependent, the hypsometry of interior basins determines the inundation and subsequent emergence of the intertidal flat area during a tidal cycle and thus governs the intertidal storage volume (Dronkers 1986; Lessa and Masselink 1995). If the relative intertidal storage (volume of intertidal basin storage/volume of the channel at mean sea level) is large, it appears that ebb dominance may occur.

Conclusions derived from the preceding studies suggest that inlets with large basin area change (and consequent large bay water surface area change) with tidal stage (bay tidal flats) are more prone to ebb dominance than inlets with constant bay water surface areas.

EXAMPLES OF INLETS/ESTUARIES WITH TIDAL VELOCITY ASYMMETRY: The following are examples of inlets and estuaries that have been documented to have tidal asymmetries:

Flood-Dominant Asymmetry Examples.

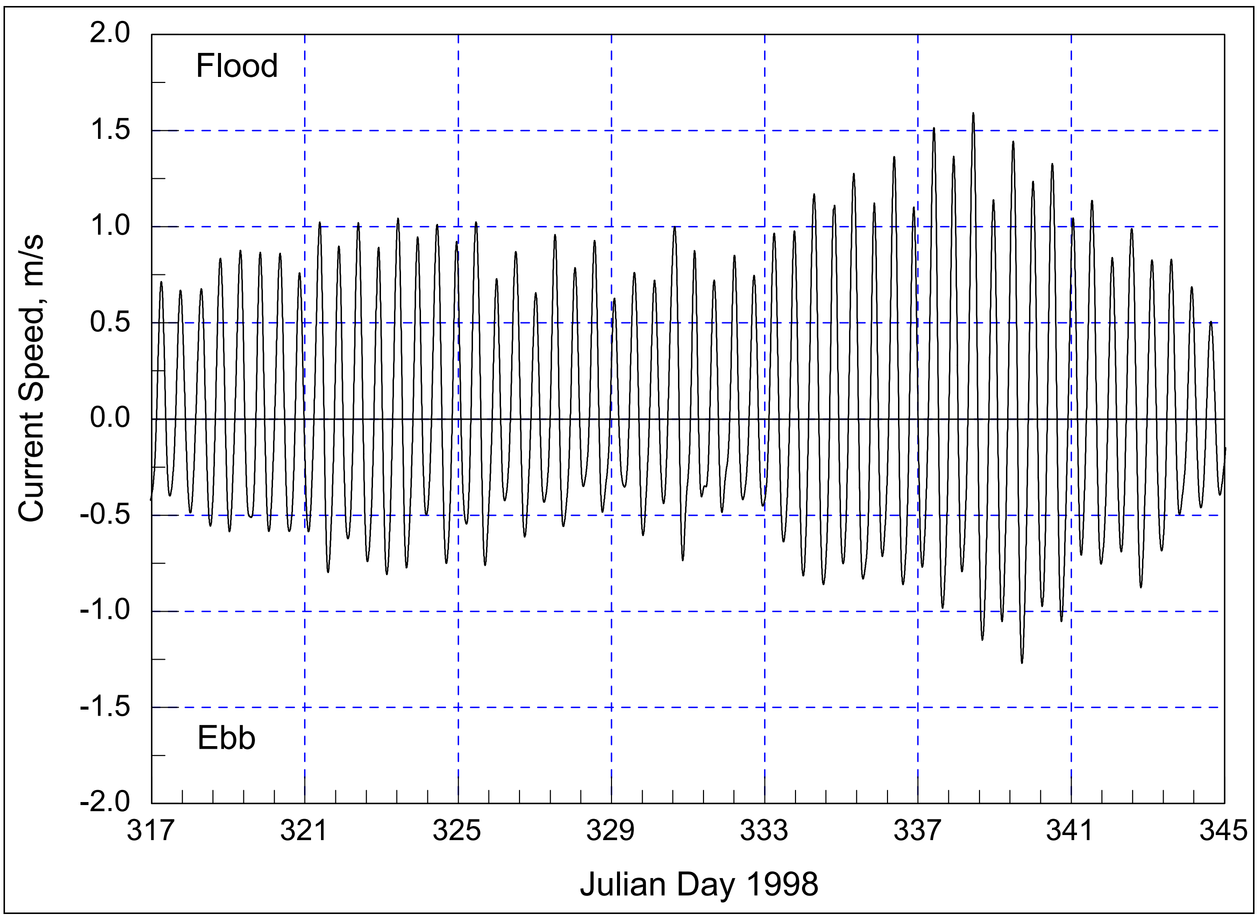
Nauset Inlet, -Cape Cod, MA (Speer and Aubrey 1985; Aubrey and Speer 1985). Nauset Inlet system is a salt marsh intersected by three major tidal channels and connected to the ocean by a natural unstabilized inlet. The offshore tide is predominantly semidiurnal (M_2) with a range of approximately 2 m. Current and sea level measurements made in 1981-1982 as documented in Aubrey and Speer (1985) show this inlet/estuary complex to be flood dominant. Although nonlinear forced tides were negligible in the ocean station, they were significantly enhanced within the inlet/estuary complex. The tidal dissipation that occurred show that the inlet/estuary complex acts as a low pass filter with larger damping rates for semidiurnal tide components than for diurnal tide components. Aubrey and Speer (1985) found that velocity asymmetry was enhanced during spring tide and that asymmetry effects virtually disappeared during neap tides.

Ogunquit, Batson, Little, Sprague, and Morse Inlets, ME (Lincoln and Fitzgerald 1988). Lincoln and Fitzgerald (1988) documented five small (50-200-m-wide and 1-3-m-deep) inlets along the Maine coast in an area of predominantly semidiurnal tides. Measurements of the current indicated the inlets experienced larger flood currents than ebb currents, with mean and maximum flood tidal currents averaging more than 20 cm/sec greater than the ebb tidal currents as measured at the inlet throat. In addition to previously documented reasons for flood dominance, another factor favoring flood dominance in these inlets was noted to be the fact that the channels were sufficiently shallow to truncate the lower portion of the ocean tide, thereby resulting in an asymmetric tide with an elongated fall duration and a shortened rise duration. In at least one case (Ogunquit Inlet), the tide range attenuation observed was postulated to be primarily a result of the tidal truncation rather than the friction in the channel. Lincoln and Fitzgerald (1988) noted that the inlets did not have well developed ebb tidal deltas and that high marsh occupied much of the back bay with very limited tidal flats (10 percent on average).

New Corpus Christi Pass (Behrens, Watson, and Mason 1977). Behrens, Watson, and Mason (1977) measured the average velocity in the inlet channel over eight tidal cycles in 1972-73 and found that the peak flood velocity exceeded the peak ebb velocity by as much as 33 percent.

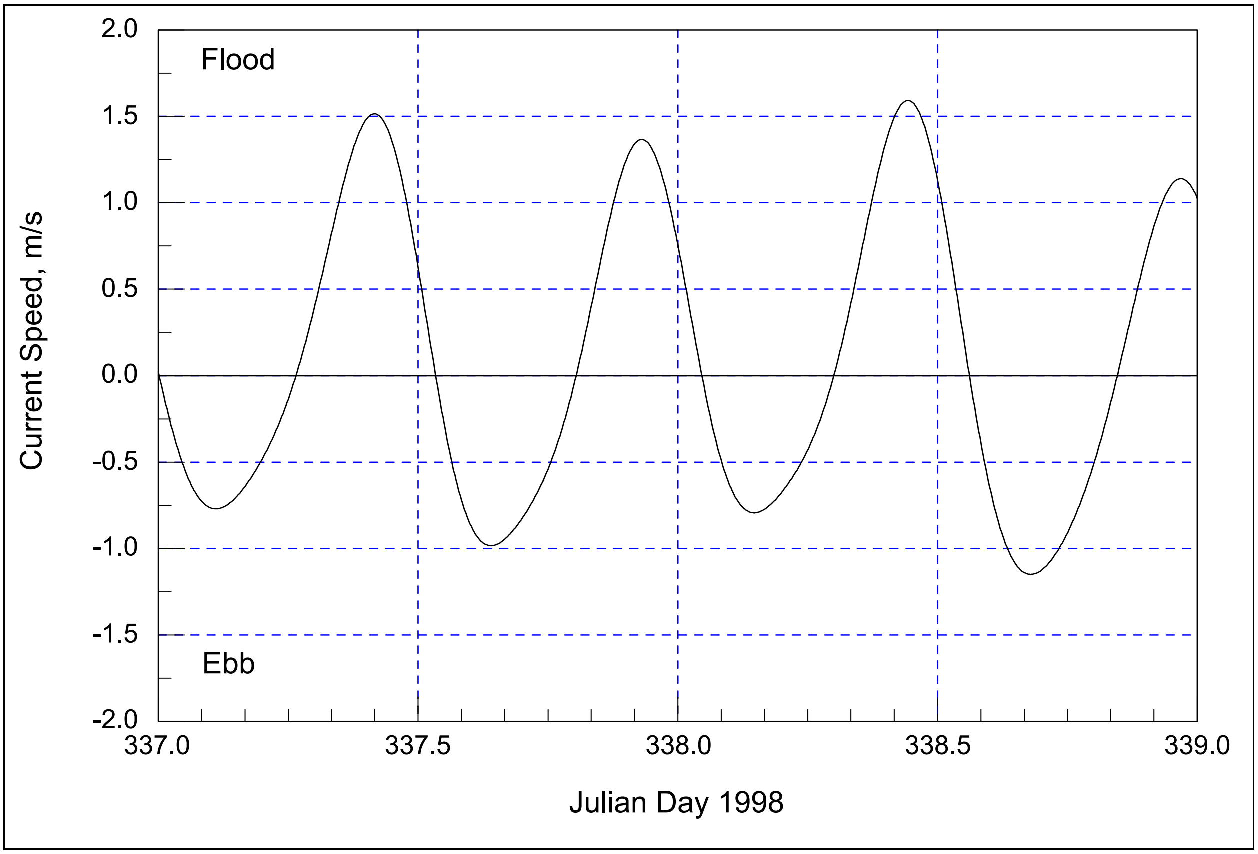
Wilson Inlet, Southwest Australia (Ranasinghe and Pattiaratchi 2000). Ranasinghe and Pattiaratchi (2000) note ebb dominance for this inlet system as determined from current measurements over a period of 30 days.

Shinnecock Inlet, New York (Militello and Kraus 2001). Current measurements were made in the inlet channel during the period of November-December 1998 which provided a record of the dominance of flood currents with the spatially averaged peak flood current magnitude on the order of 25 percent greater than the peak ebb current magnitude. Figures 7a and 7b illustrate the dominant flood current and the asymmetry in the velocity with maximum flood current exceeding maximum ebb current by about 50 percent.



a. 13 November through 10 December 1998

Figure 7. Bin-averaged current speed in Shinnecock Inlet (Continued)



b. 3-4 December 1998

Figure 7. (Concluded)

Ebb-Dominant Asymmetry Examples.

Wachapreague Inlet, Wachapreague, Virginia (Boon and Byrne 1981). Wachapreague Inlet is a deep and relatively stable inlet having large ebb delta deposits but lacking flood delta deposits (Byrne, DeAlteris, and Bullock 1974). Boon and Byrne (1981) discuss tidal current data recorded in 1978 that show ebb dominance.

North Inlet, SC (Nummedal and Humphries 1978). In measurements over a 2-year period of study (1974-1975), peak ebb velocities ranged from 20 to 156 cm/sec while peak flood velocities ranged from 24 to 128 cm/sec with peak ebb velocities exceeding peak flood velocities ranging from 22 to 32 percent in the throat of the inlet.

Price Inlet, SC (FitzGerald and Nummedal 1983). FitzGerald and Nummedal (1983) document an average ebb velocity 16 percent larger than the average flood velocity over a data set of 12 complete tidal cycles.

Swan River and Peel-Harvey estuary/inlets, southwest Australia (Ranasinghe and Pattiaratchi (2000)). Ranasinghe and Pattiaratchi (2000) note ebb dominance for these inlet systems as determined from current measurements over a period of 30 days. The tidal response of the

inlet/estuary systems was analyzed using Fourier transform techniques to determine whether the observed tidal velocity asymmetry could be explained by overtide generation.

ADDITIONAL INFORMATION: This CHETN is a product of the Inlet Geomorphology and Channel Evolution and Inlet Channels and Adjacent Shorelines Work Units of the Coastal Inlets Research Program (CIRP) being conducted at the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. For additional information on the CHETN, contact the author, Dr. Todd Walton (*Todd.L.Walton@erdc.usace.army.mil*), of the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory or Dr. Nicholas C. Kraus (601-634-2016: *Nicholas.C.Kraus@erdc.usace.army.mil*) of CHL. For information on the CIRP, contact Dr. Kraus.

This technical note should be cited as follows:

> Walton, T. L. Jr. (2002). "Tidal velocity asymmetry at inlets," ERDC/CHL CHETN IV-47. U.S. Army Engineer Research and Development Center, Vicksburg, MS. *http://chl.wes.army.mil/library/publications/chetn*

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